CRC for
Water Sensitive Cities

Quantifying sediment export from an urban development site: Heron Park, Western Australia

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Foreword

The Sediment Task Force have long been aware that erosion, sediment runoff and sand drift during sub-divisional works, housing and commercial construction and public works (including road construction) are significant contributors to sedimentation in stormwater infrastructure, and subsequently waterways and wetlands, when legislative requirements are not complied with and/or enforced.

Due to a paucity of scientific research on the quantities of soil and building sand run-off from sites during urban development, the Sediment Task Force engaged the University of Western Australia (UWA) in 2016 to undertake this innovative research. This research was also initiated due to the building industry representatives on the Task Force requesting quantification around the impact of sediment loss, to assist them to determine if, and how much, sedimentation resulting from urban development was an industry issue.

This research aimed to gain insights into the mechanisms that may exacerbate or ameliorate the discharge of sediment from subdivision, building and construction sites, and to understand the issues behind the problem. This included seeking clarification as to how sand and other particulate materials entering the stormwater management network contribute to the issue and the quantity and quality of water-borne sediment generated under different hydrological conditions.

On behalf of the Task Force, I would like to express a very heartfelt thank you to Professor Carolyn Oldham and Dr. Carlos Ocampo from the University of Western Australia and the Cooperative Research Centre for Water Sensitive Cities (CRCWSC) and to their post-graduate students Fraser Eynon, Hannah Sutton, Andrew van de Ven, and Yilin Lin for their expertise, dedication, hard work and commitment to this important research.

Our appreciation also goes to our research sponsors; the Department of Biodiversity, Conservation and Attractions, the Water Corporation, Main Roads (WA), the Cities of Armadale, Gosnells and Kwinana, the West Australian Local Government Association (WALGA), South Eastern Regional Centre Urban Landcare (SERCUL) and the Cooperative Research Centre for Water Sensitive Cities.

Much gratitude is expressed to the Satterley Property Group for enabling this research to be undertaken and to their on-site staff and contractors for supporting UWA's research students and ensuring the monitoring equipment remained safe and sensors were successfully relocated as site works progressed.

On behalf of the Sediment Task Force and Perth NRM, I thank you for your interest in this research and trust that it will assist you in your endeavours to protect the environment by improving water quality outcomes.

Yours faithfully,

Bronwyn Scallan, Sediment Task Force Coordinator

Perth NRM

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Department of **Biodiversity, Conservation and Attractions**

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Executive summary

Context

This report summarises findings from a research project commissioned by the Sediment Task Force, which is a partnership between Perth Natural Resource Management (NRM), the Department of Biodiversity, Conservation, and Attractions (DBCA) and other government environmental managers and enforcement agencies, leading housing industry groups, local government authorities, and community groups. The Sediment Task Force represents a collaborative approach to develop solutions that prevent sediment run-off, particularly, but not exclusively, from building sites.

This project was established to provide field data that identifies activities producing water-borne sediment, and the conditions under which that sediment is discharged from an urban development site, where land is being sub-divided, landscaped, and roads and houses constructed. This project specifically aimed to:

- Explore approaches and test methodologies for quantifying sediment export in urban drains;
- Quantify sediment export from an exemplar urban development site, across both storm event and baseflow (non-storm) conditions; and
- Recommend appropriate measures for reducing sediment export in future development activities.

Soil is eroded from land development sites, due to disturbance of the land surface and exposure of the topsoil (or fill), followed by suspension and transport by wind and/or water. Soil may be blown onto roads and drains, then washed down during storm events, which can also directly mobilise soils from development sites into the drainage system. We use the term “soil” to indicate the material sitting at the surface of a site, “dust” to indicate air-borne soils, and “sediment” to indicate water-borne soils.

In a review of existing planning, statutory and policy mechanisms for controlling and enforcing the management of erosion and sedimentation from the Southern River Catchment land development in Western Australia (WA), Essential Environmental Services (ESS, 2010) suggested that determination of when and how sediment enters the downstream system was necessary to justify any additional measures or costs to be imposed on developers and/or builders to address the issue.

Stormwater-borne sediment creates challenges for receiving waters, such as the deposition of the sediment itself as well as the transport of sediment-bound contaminants. The export of suspended sediment in stormwater runoff from construction sites has been estimated to be 10-20 times greater, per unit area, than from agricultural land and 1000-2000 times greater than from forested land (USEPA 2000). It is therefore imperative that sediment export from construction sites is monitored and regulated in urban stormwater systems.

The study site used for this project was a new 27.5 ha land development by Satterley, in Harrisdale, Western Australia. The pre-development landscape was pastoral land that had experienced very little change in the previous decades. During the research project, several stages of released land underwent civil works, individual lot development and finally house construction. The development site has an open drain running through the centre, that discharges into Balannup drain, which then flows into the Southern and Canning Rivers; this setting provided an opportunity to monitor sediment discharged from different stages of urban development.

Turbidity and total suspended solids relationship

To quantify sediment loads being discharged from areas at different development stages, three steps were required:

- Establish a relationship between continuous *in situ* measurements of turbidity, and total suspended solids concentrations (TSS), as measured in discrete water samples;
- Monitor storm events and base flow conditions, for both turbidity and flow rates; and
- Calculate sediment load discharged during storm events and baseflow conditions.

To establish a relationship between turbidity and TSS concentrations, 20 storm events were monitored in both 2017 and 2019, along with baseflow conditions between the events; no monitoring was undertaken in 2018 which enabled monitoring to cover a range of development activities. The project established a clear relationship between turbidity and TSS concentrations during active phases of urban development. Using the established relationship, we could use continuous turbidity measurements to quantify sediment loads being discharged from active urban development sites.

Estimated sediment export loads

Three sites were monitored across 2017 and 2019, with S1 located at the inlet of Heron Park, S2 at the outlet of Stage 23, and S5 located close to the outlet of the development. Water levels and turbidity was measured at high frequency, and converted to flow rate (via a rating curve) and suspended sediment concentration (via the established turbidity – TSS relationship). Sediment loads could thus be estimated across a range of hydrological conditions. Active development was classified into two activities: civil works and lot development, including house construction, and sediment discharge was quantified for both of these activities.

No statistically significant differences in sediment discharge were observed between the two activities. This finding may appear counter-intuitive, as erosion of individual piles of sand from developing lots is highly visible after storm events (the pile has decreased in height). This highlights that sand erosion across a large expanse of sand undergoing civil works is less visible, but may be significant in total, and therefore becomes a shared responsibility across multiple stakeholders (e.g. land developer, contractors). This shared responsibility has implications for the management of water-borne sediment and is discussed below.

Given the above finding, all land was assessed as having the same potential source of water-borne sediment, given a known area of exposed sand. Therefore, the rate of sediment discharge between sampling sites, during storm events and under baseflow conditions, was calculated per square meter of exposed sand present in the sub-catchment. During storm events, sediment was discharged at a rate of 0.005 kg/day/m^2 sand.

When baseflow was low, from February – July, sediment was discharged at a rate of 0.002 kg/day/m^2 sand. Interestingly, as baseflow started to increase from August, most likely due to intersection with seasonally high groundwater (Ocampo et al 2017, Ocampo and Oldham 2017), there was a concomitant increase in sediment discharge to 0.014 kg/day/m^2 sand. This increased sediment discharge was likely due to higher volumes of water flushing out sediment previously deposited into the system. It was also observed on-site that there was increased delivery and accumulation of exposed sand in the sub-catchments, in anticipation of construction work under spring/summer conditions.

These measured rates of sediment discharge amount to approximately 17,000 kg/ha of exposed sand/year. This can be compared to measured sediment fluxes of 350 kg/ha/year from an agricultural (grazing) catchment in Western Australia (McKergow et al. 2001); Heron Park was discharging sediment at approximately 50 times the rate from agricultural land.

Across the Heron Park site, the measured sediment discharge rate amounted to a total of 460,000 kg (290 m^3) in 2017, and 306,000 kg (190 m^3) in 2019. The cost to the developer of importing (and therefore losing) 200-300 m^3 of building sand per year is only $5000-$7500 (Peet Ltd, personal communication). In contrast, the cost borne by local councils can reach up to $600,000 per year for managing water-borne sediment discharged from new subdivisions (www.perthnrm.com/2019/06/stf-article-costofcontrol, accessed February 27 2020). Other councils have reported dredging costs of $15 – $80 per tonne of sediment, depending on the ease of access to the site and difficulty of the dredge. Using this costing, if all the sediment discharged along the Heron Park drain in 2017 and 2019 (estimated at 766 tonnes) were released to waterways, it would cost approximately $12,000 – $60,000 to remove/dredge.

McKergow et al. (2001) demonstrated that, with appropriate planting adjacent to agricultural drainage lines, the sediment discharge can be reduced to almost nothing. This aligns with advice from sediment management manuals from Australia and overseas, that recommend temporary planting of exposed areas and drainage lines, right at the start of land disturbance for urban development. The retention of sand on-site that would otherwise be lost to erosion, would provide an additional resource for use in the development, and would significantly reduce the cost to local councils and the Water Corporation of dredging sediment from downstream drains and waterways.

Recommendations for improved management of sediment

The data collected during this research project, and previously published work, has highlighted that active management of water-borne sediment is essential during all phases of land development, from initial earthworks, through to civil works, landscaping and finally house construction.

Currently, there is private benefit from urban development, yet the cost of expensive on-going management of water-borne sediment arising from this urban development, is predominantly borne by the local and state government, and therefore the public. This private benefit – public cost needs to be further examined, as best practice sediment management practices are considered.

Management practices that prevent both air-borne and water-borne soil loss should be implemented. For example, the rapid, temporary revegetation of exposed soil, or retention of natural vegetation, is recommended at all stages of development. The implementation of temporary vegetated swales at drain outlets during development, provides an end-of-pipe prevention of sediment discharge to downstream waters. A comprehensive list of appropriate sediment management practices, across different stages of urban development, was provided by Essential Environmental Services (ESS,2010).

Recommendations for further work

This work has highlighted some key data and knowledge gaps, and the need to consolidate the findings of the project. There are two ways to achieve this: 1) through monitoring activities and 2) through numerical modelling.

Monitoring is essential to determine, in order of priority:

- Sediment discharge from land undergoing bulk earth works. This monitoring activity would require a new study site.
- Event-based sediment discharge when baseflows are high. At present no data exists for this condition. In addition, confirmation is needed that the turbidity-TSS correlation established for storm events from construction activities, is still applicable to high baseflow conditions during the spring. This monitoring could be undertaken at Heron Park.

- Sediment accumulation and export associated with civil works areas with exposed sand. Short-term targeted monitoring should be undertaken, of sediment accumulation and export, during and after completion of civil works areas, with exposed sand. This land use will be present until the completion of the Heron Park development, and thus provides opportunities to build on the findings of this report.
- Sediment transport and export along the minor drainage network and side pits at Heron Park. This includes short-term monitoring at times when baseflow is high.

Modelling of in-drain sediment transport could determine any bedload sediment movement, that may occur in addition to the transport of suspended sediment. It is currently unknown what magnitude of storm events is required to flush bedload sediment out of the system. A numerical model would allow exploration of the effect of different hydrological conditions on total sediment transport (suspended and bedload).

1. The challenge

Soil is eroded from urban development sites, due to disturbance of the land surface and exposure of the topsoil (or fill), followed by suspension and transport by wind and/or water. Soil may be blown onto roads and drains, then washed down during storm events, which can also directly mobilise soils from development sites into the drainage system. Note that we use the term “soil” to indicate the material sitting at the surface of a site, “dust” to indicate air-borne soils, and “sediment” to indicate water-borne soils.

Air-borne dust is highly visible to the public, impacts on air quality and amenity, and is subject to significant monitoring and relatively effective regulation. In contrast, water-borne sediment is typically visible during peak storm events when public scrutiny is reduced and monitoring becomes challenging. Discharged sediment may be evident downstream after a storm event, however attributing this to a specific stakeholder or development activity can be difficult, and thus regulation of sediment discharge remains a challenge. This is despite a number of regulatory instruments already in place for water-borne sediment discharges (Essential Environmental Services (ESS), 2010).

In a review of existing planning, statutory and policy mechanisms for controlling and enforcing the management of erosion and sedimentation from the Southern River Catchment land development in WA, ESS (2010) recommended identification of the activity and area from which most sediment was being transported into receiving waters, so that responsibility for management of the issue can be ascertained. ESS (2010) suggested that determination of when and how sediment enters the downstream system was necessary to justify any additional measures or costs to be imposed on developers and/or builders to address the issue.

The development activities that typically cause disturbance of the topsoil/fill, identified by ESS (2010) are:

- Bulk earthworks (as part of subdivision);
- Subsequent to bulk earthworks and arising from construction and installation of infrastructure (road, drainage and sewer construction);
- Subsequent to subdivision and prior to house construction (vacant lots, waiting to be sold or vacant lots, waiting to be built on);
- Site preparation for building;
- Building of the dwelling; or
- After construction of the house and prior to landscaping.

This report summarises the findings of a research project, commissioned by the Sediment Task Force, to provide field data that identifies activities producing water-borne sediment, and the conditions under which that sediment is discharged from the development site.

1.1 Downstream impact of water-borne sediment

Stormwater-borne sediment creates challenges for receiving waters, such as the deposition of the sediment itself (Atasoy et al. 2006; Minella et al. 2008), as well as the transport of sediment-bound contaminants (Trenouth et al. 2013; Anta et al. 2006; Wakida et al. 2014). The presence of suspended sediment in aquatic ecosystems has significant effects on the community structure, diversity, density, biomass, growth, rates of reproduction, and mortality of biota (Henley et al. 2000). A high concentration of total suspended solids (TSS) can negatively impact periphyton (Gao et al. 2008; Henley et al. 2000), and reduces light available for phytoplankton photosynthesis (Henley et al. 2000). These effects on the primary trophic levels of aquatic ecosystems mean that the entire food web is affected both directly and indirectly. Furthermore, as TSS settles on the remaining macrophytes, the sediment forms a physical barrier preventing higher order consumers from consuming them (Henley et al. 2000).

In addition to ecological impacts in receiving waters, sand and other particulate materials that enter the stormwater management network can impact stormwater assets through:

- increased flooding incidents of roads, houses/buildings and parks, due to blocked or full stormwater management systems;
- reduced amenity of parks containing stormwater management systems;
- reduced function and amenity of at-source water sensitive urban design stormwater management systems (e.g. pervious paving, tree pits, biofilters and infiltration cells); and
- increased maintenance costs of the stormwater management network and the receiving parks and water bodies.

The export of suspended sediment in stormwater runoff from construction sites has been estimated to be 10-20 times greater, per unit area, than from agricultural land and 1000-2000 times greater than from forested land (USEPA 2000). It is therefore imperative that sediment export from construction sites is monitored and regulated in urban stormwater systems.

1.2 Measurement of water-borne sediment concentration

The concentration of water-borne sediment is measured in a water sample as total suspended solids (TSS). Monitoring of TSS requires grab water sampling (whether by hand or via an autosampler), followed by subsequent analysis in the laboratory. The water sampling and analysis are time-consuming and costly, and the data are typically collected at frequencies too low to adequately characterise TSS dynamics across storm events (Jones et al., 2011). Consequently, there is a paucity of spatial and temporal data during storm events when TSS concentrations are highest (Jones et al., 2011).

The use of turbidity as a surrogate for TSS concentrations has been investigated internationally for several decades. Turbidity is a measure of the amount of light scattered by suspended particles in a water sample, and can be measured *in situ* at high frequency and low cost (Jones et al., 2011), opening the possibility for easy monitoring of water-borne sediment, even during storm events. However, the relationship between turbidity and TSS concentrations varies across soil type and hydrology (Ruzycki et al., 2014), and prior to this project, the relationship had rarely been quantified for the soils and conditions found in Perth. In a review of existing data, Sutton (2017) found only two drains in Perth with adequate data to derive this relationship. If a predictive relationship between turbidity and TSS could be demonstrated in the Heron Park drain, this would significantly reduce the need for costly monitoring and analysis.

1.3 Regulation of water-borne sediment

ESS (2010) provided an excellent overview of the regulatory framework of water-borne sediment in Australia, and specifically in Western Australia. They concluded that there are already in place sufficient mechanisms to enforce the management and control of erosion and transport of sediment from urban development on the Swan Coastal Plain. They found that such mechanisms are available, and need to be employed, at each stage of the planning and development process. However, they noted that the most effective were expected to be:

- Conditions of subdivision
- Condition of development
- Building licence requirements; and
- The enforcement of the local laws relating to erosion and sediment control.

However, ESS (2010) found that the enforcement of these mechanisms could be improved by:

- increasing the level of knowledge regarding the need for better erosion and sediment control across industry and the general community, including political or strong leadership;
- consistent application of conditions of subdivision and development as well as building license requirements, which would necessitate the preparation and implementation of erosion and sediment control plans and dust management plans;
- clear standards of performance to be achieved via erosion and sediment control efforts at all stages of the development process, appropriate to the risk factors on site and which contain measures for ongoing and adaptive management;
- comprehensive guidelines as well as simple information to aid the development of effective management plans and building site practices; and
- well-resourced enforcement officers with transparent audit standards and the ability to issue fines.

A recent review of the regulatory environment confirmed that there have been minimal changes in the last decade and the 2010 findings were still valid in 2020 (S. Shepherd, *personal communication*).

1.4 Aim and scope of work

Following on from ESS (2010), this project aimed to:

- Explore approaches and test methodologies for quantifying sediment export in urban drains;
- Quantify sediment export at the Heron Park urban development site under a range of construction activities and storm events; and
- Recommend specific appropriate measures for reducing sediment export in future construction activities.

2. Study site

The study site for this project was a new land development in Harrisdale, Western Australia. The development has an approximate area of 27.5 ha. The pre-development landscape was pastoral land that had experienced very little change in the previous decades. Development commenced prior to the start of the research project, and bulk earthworks had been completed and a small area in the east of the site has been developed (Figure 1).

The site was split into ten stages by the developer. Throughout the 2017 and 2019 study period, the developer release stages and their lots for purchase and subsequent residential construction. Before the release of the stages, civil works were completed by a single subcontractor. These civil works were characterised by small-scale earthworks, the installation of roads, and the installation of underground services and drainage. Housing construction would proceed after the release of individual lots; different building companies may undertake construction on each lot. Over the research project, two stages were substantially developed under Phase 2 of the Heron Park development: Stage 23 (released early 2017 and 80% completed by October 2017) and Stage 24 (released late October 2017 and 90% completed by December 2019). Other stages for future release were also progressed through civil works.

The development site has an open drain running through the centre and one branch drain (Figure 1). The open drain enters the site from a small already-established urban catchment area (Stages 11 to 16 of Heron Park); the drain running through Heron Park was designed to receive water from subsoil pipes that control groundwater levels, as well as convey surface flows (JDA 2014, 2015) acting as a storage swale and incorporating filter media to attenuate nutrients. The drain discharges into Balannup drain, which then flows into the Southern and Canning Rivers. We note that downstream sediment control measures were in place in Balannup drain, and the total sediment export from Heron Park to the Southern and Canning Rivers was outside the scope of this study.

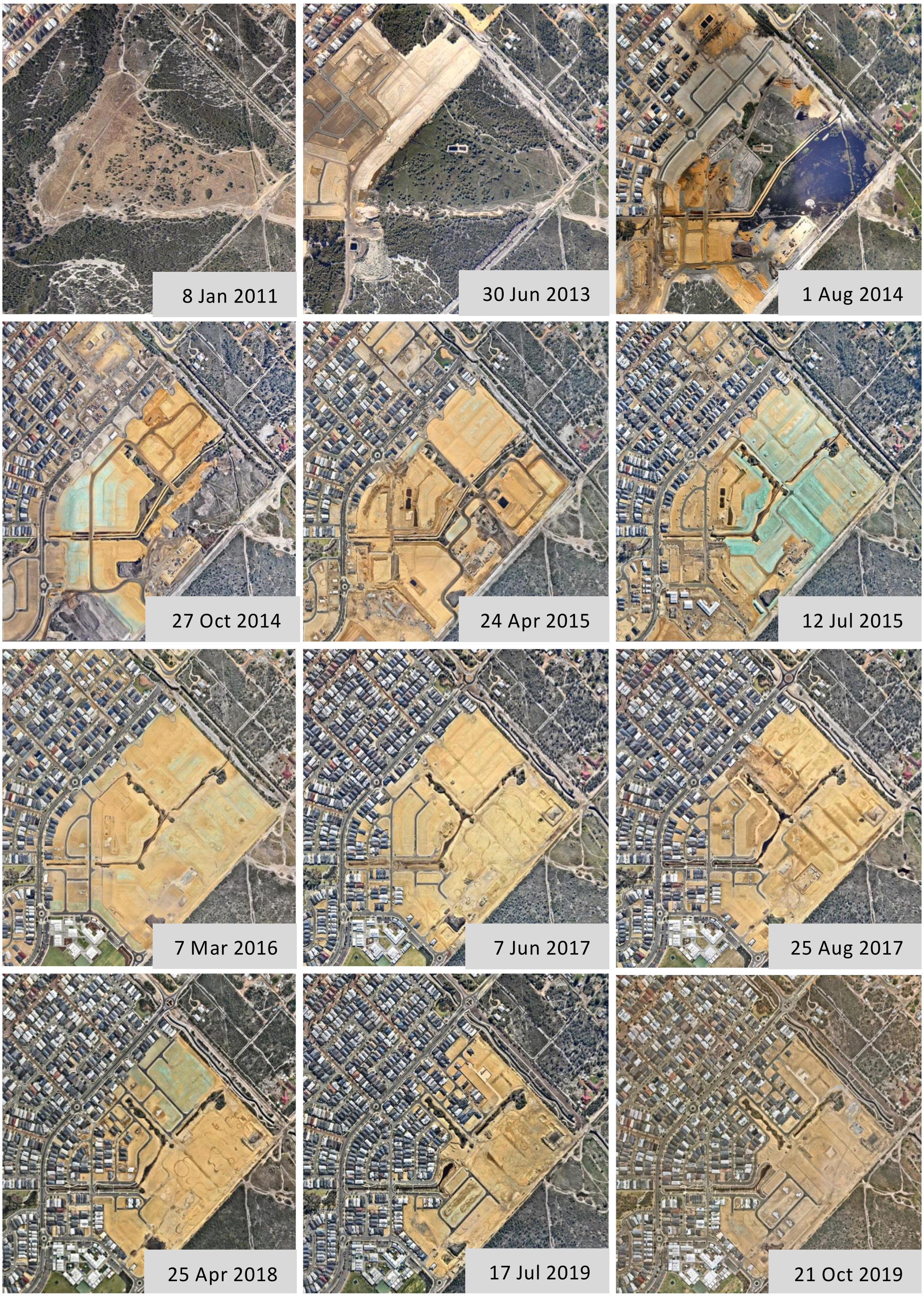

Figure 1 Heron Park land development, from 2011 - present. Photos from Nearmap.

3. Methodology

3.1 Monitoring approach

This project focused on monitoring water-borne sediment discharged from lots and land parcels undergoing development. The development of individual lots in a development occurs at different time and places. It is therefore challenging to effectively and efficiently characterise lot-scale export of water-borne sediment. Consequently, this project monitored water-borne sediment entering and exiting the drain, rather than being discharged from a lot (Figure 2).

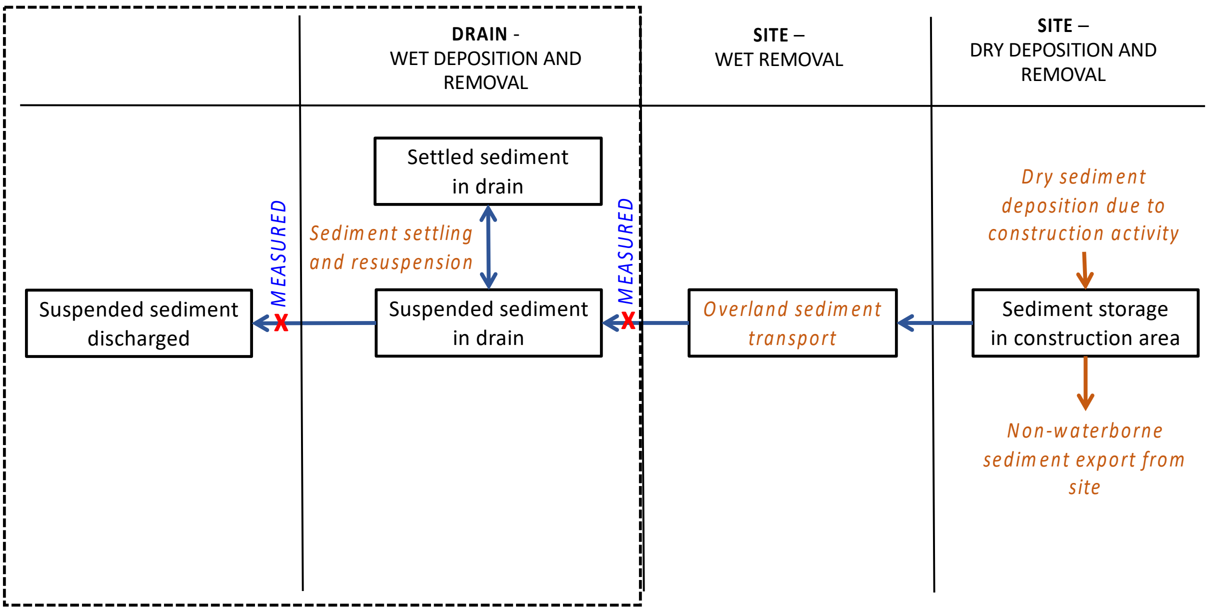

Figure 2 Schematic of soil erosion from land development sites, incorporating air-borne erosion and water-borne erosion. This project focused on quantifying water-borne erosion.

Parcels of land were incrementally released for development over 2017 – 2019. Sections of drain were defined, that received water from land parcels undergoing different stages of development. Land within each parcel (or sub-catchment) was classified as either a) areas with exposed sand (civil works, vacant lots, care and maintenance), or b) areas that were developed or hard surfaces and therefore had minimal exposed sand (residential housing, roads). Four sections of drain were defined, with sampling sites established upstream and downstream of each section (Figure 3). In 2017, sampling sites S1, S2, and S5 were monitored; at this time Stage 23 (draining to the drain section bounded by sampling sites S1 and S2) was undergoing house construction, while Stages 24, 27, 28 and 29 (draining to the drain section bounded by sampling sites S2 and S4) were either undergoing civil works, or were under care and maintenance (Figure 4). In 2019, sampling sites S1, S2, S3 and S5 were monitored; by this time, almost all of Stage 23 was fully developed, Stages 24, 26, 28 and 30 were partially developed, and Stages 27, 29, 31 and 32 were undergoing civil works. The total areas of adjacent stages that contribute water (and sediment) to each section of drain, and also the areas of exposed sand in those stages, were estimated using Nearmap^{TM} photographs (Table 1).

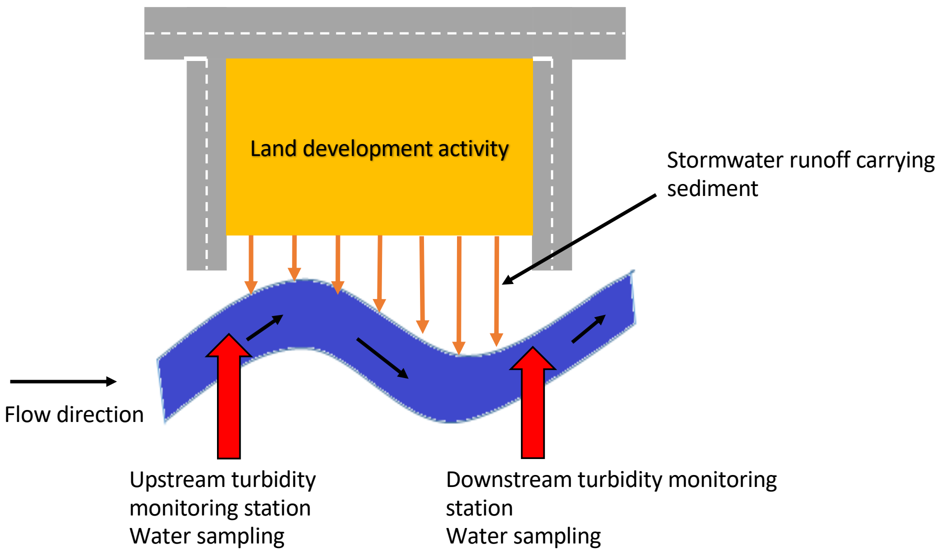

Figure 3 Monitoring approach used for the project; measuring turbidity upstream and downstream of a specific land development activity.

Figure 4 Sampling sites where turbidity and/or water levels were monitored, and water samples collected for analysis of total suspended solids in a) 2017 and b) 2019. Shaded areas indicate land stages progressively developed 2017 - 2019. Light green area indicates the detention storage swales draining across the site.

Table 1 Areas of sub-catchments discharging to sections of drain, delineated by sampling stations S1 to S5, and the proportions of those sub-catchments with exposed sand that is vulnerable to erosion.

Sub-catchment	Area (m^2)	Proportion of sub-catchment (%)	Development activity
July 2017			
Stage 23	44,239		House construction
Exposed sand	17,227	39	
Stages 24, 26-32	257,624		Civil works, care and maintenance
Exposed sand	242,341	94	
July 2019			
Stage 23	44,239		Fully developed lots
Exposed lot sand, including vegetated drain	2,944	7	
Stage 24, 28	76,135		House construction
Exposed sand	28,462	37	
Stages 27, 29	55,733		Civil works
Exposed sand	55,733	100	
Stages 26, 30, 31, 32	100,825		Developed lots, care and maintenance
Exposed sand	86,283	86	
Total Heron Park development	298,295		
Total exposed sand July 2017	259,568	87	
Total exposed sand July 2019	170,850	57	

Water level, turbidity, and total suspended solids concentration were measured at different times across the five monitoring sites in 2017 and 2019, to capture baseflow and storm flow sediment discharge from the different sub-catchments. The periods of monitoring at each site, and the frequency of monitoring, are shown in Table 2.

Table 2 Parameters measured over the sampling program.

Sampling site	Parameter	Dates	Sampling frequency
S1	Water level Water velocity	13th May– 22nd May 2017 20th June - 26th June 2017 30th June – 2nd August 2017 24th June – 6th November 2019 19th July – 20th July 2019 3rd October – 5th October 2019	Automatic; 10-minute Automatic; 5-minute Automatic; 2-minute
S1	Turbidity	13th May – 15th May 16th May – 21st May 21st June – 25th June 2017 30th June – 3rd July 2017 4th July – 8th July 2017 20th July - 24th July 2017 26th July – 27th July 2017 29th July – 2nd August 2017 17th November – 21st November 2017	Automatic; 2-minute
S1	Total suspended solids	14th May 2017 21st June 2017 1st July 2017 29th July 2017 24th June 2019 29th June 2019 2nd July 2019 4th July 2019 20th July 2019	Manual grab sample
S2	Water level Water velocity	13th May – 22nd May 20th June - 26th June 2017 30th June – 2nd August 2017 24th June – 6th November 2019 19th July – 20th July 2017	Automatic; 10-minute Automatic; 5-minute Automatic; 2-minute
S2	Turbidity	13th May – 15th May 2017 16th May – 21st May 2017 21st June - 25th June 2017 30th June – 3rd July 2017	Automatic; 2-minute

		4th July – 8th July 2017 20th July - 24th July 2017 24th July – 1st August 2017	
	Total suspended solids	14th May 2017 21st June 2017 1st July 2017 29th July 2017 24th June 2019 29th June 2019 2nd July 2019 4th July 2019 20th July 2019	Manual grab sample
S5	Water level Water velocity*	13th May – 26th June 2017 20th Sep – 29th September 2017 24th June – 10th October 2019 6th August 2019 3rd October – 5th October 2019	Automatic; 10-minute Automatic; 5-minute Automatic; 2-minute
S5	Total suspended solids	14th May 2017 21st June 2017 1st July 2017 29th July 20174th July 2019 19th July 2019 31th July 2019 3rd August 2019 6th August 2019	Manual grab sample;

* Water velocity was measured at one culvert upstream of the actual S5 location.

3.2 Measurement of rainfall, water level and estimation of flow

A rain gauge was deployed on site, and logged every 0.2 millimetres of rain. This ensured that we quantified localised rainfall. The Jandakot Airport station (Bureau of Meteorology, Station Number 09172) also provided rainfall and meteorological data for the area.

Water level loggers (Solinst LT 3001, absolute pressure) were deployed at selected locations in culvert pipes (0.45 m diameter) for stations S1-S3 and the central stormwater channel at station S5; water levels were sampled at variable intervals ranging from 5 to 10 minutes during deployment periods (Table 2). Air pressure (atmospheric) data was used to remove barometric effect on sensor water level readings.

Acoustic doppler velocimeters (Sontek-IQ and Starflow-Unidata) were used to measure flow rates across a few storms events (Table 2), and a relationship established between flow rates and water levels (i.e. a flow rating curve). Using this rating curve, stormflow and baseflow hydrographs were obtained. These preliminary curves covered low and mid flow conditions at each station (e.g. flow occupies less than half pipe diameter); higher flow values were obtained using rating equations curves for observed high levels at each culvert.

3.3 Measurement of TSS concentration and estimation of TSS load

The concentration of total suspended solids was measured from collected water samples; however these could not achieve the same temporal resolution as the flow data. Turbidity, which is measured using in situ sensors and therefore is able to achieve high temporal resolution, has been used as a proxy for TSS with varying degrees of success (Gao et al. 2008; Gippel 1989; Holliday et al. 2003; Minella et al. 2008). These studies showed that the relationship between TSS and turbidity, and the strength of this relationship, are highly variable. Sutton (2017) demonstrated that clear relationships existed between turbidity and TSS in two Perth urban catchments. Turbidity was therefore measured in the Heron Park stormwater drain every 5 to 15 minutes under baseflow and storm flow conditions. TSS was measured from water samples collected across a range of flow conditions, and the relationship between measured TSS and monitored turbidity was characterised.

Water samples were collected at the field sites for TSS analysis, transported back to the laboratory and frozen until analysis for TSS (APHA 2540D). Samples were subsequently thawed at room temperature, and the sample bottle shaken to ensure homogenisation of the sample (Li 2019). Filter papers (2 μm) were weighed. Three sub-samples (200 mL) were removed from the bottle and filtered via vacuum filtration. The filter papers with retained sediments were placed on a baking tray, and oven dried at 104 °C. Each filter paper with residue, was again weighed, and the mass of sediment retained by the filter was determined (Li 2019). The mass of sediment divided by the water sample volume provided the concentration of total suspended solids. The measured TSS concentrations (mg/L) were then correlated with corresponding turbidity measurements (NTU).

To calculate TSS loads, both TSS concentrations (as determined from turbidity data) and flow rates were measured in the Heron Park drain. The difference in total suspended solid (TSS) load between two locations in the drainage network provides an estimate of sediment transport from construction activities undertaken between the two locations, and also from remobilisation of sediment during large storms that was deposited by earlier smaller storms in that section of the drain.

4. Findings

4.1 Flow rating

The flow rating used corrected water levels and mean flow velocity measurements to obtain discharge, using the standard Area-Velocity method.

Water level data (after barometric correction) was converted into water depth in pipes (e.g. at S1 and S2 station culverts) and in the open drain at a control section in S5 (concrete slabs were placed across the drain). All water depths were checked against manual readings with a metal ruler. Water depth at S5 was related to Australian Height Datum (AHD) after surveying the drain with an RTK-GPS (City of Armadale).

Flow rating activity was limited to a few events in 2019 (Table 2). Figure 5 shows mean velocity recorded by the IQ-pipe flow meter (Sontek Inc) for a small event on 19th July 2019 at S1 station. The water depth rose from 0.19 m to a peak of 0.28 m (e.g. partially-full pipe flow with downstream control). Velocity variability across events, indicated downstream controls over a short period of time, corresponding to the rising limb of the hydrographs (Figure 5) as the pipe exceeded its half depth value. Maximum values for mean flow velocity across stations ranged from 0.3 m/s to 0.6 m/s.

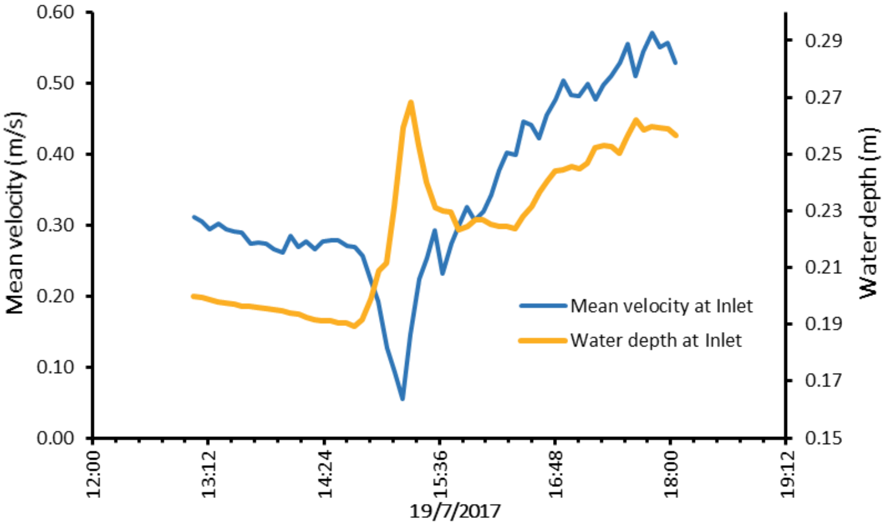

Figure 5 Mean velocity and water depth for event on 19th July 2017 at station S1. The decrease in water velocity just after 15:00 corresponded to the establishment of downstream control during peak water levels.

The preliminary rating is insufficient to the establishment of proper rating curves; this was reflected by low R^2 values (~ 0.7) and attributed to downstream controls by high water levels at the culvert's pipe outlets. However, peak discharge estimates by the rating equations were in close proximity to those used in the design of the landscaped detention storage swales between S1 and S2 stations; these discharges were 220 L/s and 300 L/s for the 1-yr ARI and 5-yr ARI events respectively. These estimates of flow discharge are sufficient for the computation of sediment loads; uncertainties associated with these values are not expected to change sediment load interpretations. More work is required to improve rating for the sites; this should be accomplished by simultaneous monitoring of a large event across all stations.

4.2 TSS and turbidity relationships

Turbidity measurements cannot directly indicate the concentration of TSS, as it may be affected by coloured dissolved organic substances (Holliday et al. 2003); under these circumstances light absorption due to colour may be greater than light scattering by particles, and turbidity readings may be lower than expected relative to the TSS concentrations (Chen et al. 2007, Li 2019).

Turbidity is also dependent on particle size and shape (Gippel 1989), particle size distribution (Yao et al. 2014), and light reflectivity of particles (Bhargava and Mariam 1991). Therefore, the correlation between turbidity and TSS concentration may be site specific (due to different soil types) and may vary with adjacent land use and storm rainfall intensity (Li 2019). Strong correlations between turbidity and TSS concentrations, have previously been demonstrated at a variety of sites around the world (Line and White 2001; Williamson and Crawford 2011; Rügner et al. 2013), and turbidity has been used successfully to evaluate TSS concentration and sediment loads in rivers (Daphne et al. 2011), streams (Gippel 1989) and catchments (Gao et al. 2008; Line et al. 2013), and stormwater runoff (Memon et al. 2015; Sutton 2017). Sutton (2017) found for two urban catchments in Perth, that the relationship between TSS and turbidity is stronger immediately after a storm, and also for higher intensity storms.

In 2017, water samples were collected for TSS measurement and turbidity was monitored across a range of hydrological conditions, at Sites S1, S2 and S3. During this time, the land parcel draining to S2 was undergoing residential construction, and the land parcel draining to S3 was undergoing civil works. In 2019, water samples for TSS measurement and turbidity monitoring were collected at Sites S1, S2, S3, S4, and S5. In 2019, S4 and S5 received water from stages undergoing civil works, S3 received water from stages undergoing residential construction, and while S2 received water from stages that were fully developed.

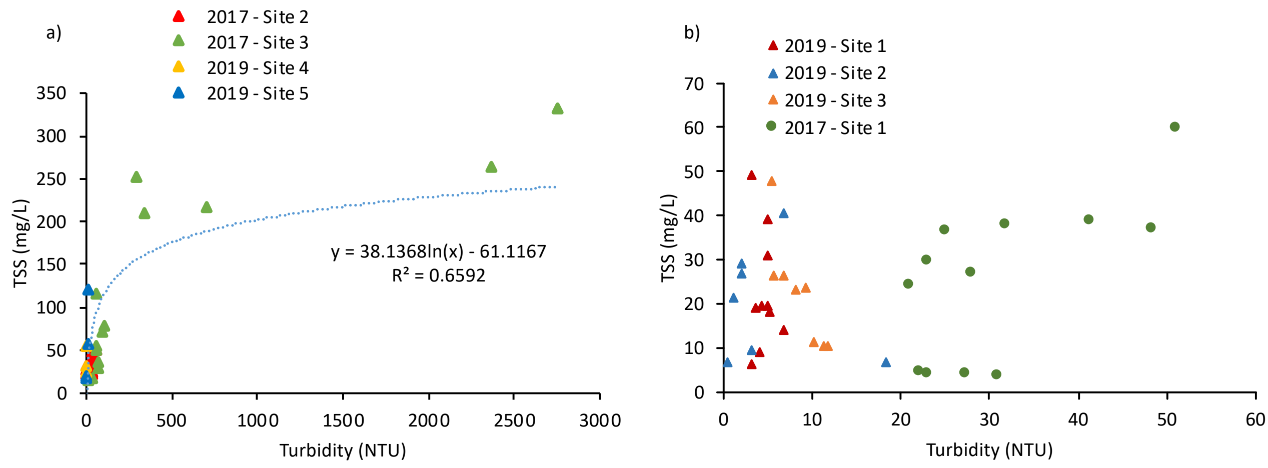

Figure 6 Relationship between total suspended solids (TSS) and turbidity, measured in 2017 and 2019, in a) drains receiving water from areas under construction, and b) drains receiving water from areas no longer under construction. Lots on the latter areas had been fully constructed and landscaped. Note the large differences in scale on both the x- and y-axes.

One of the striking observations was that sections of the drain that received discharge from stages undergoing civil works (Figure 6a) experienced different turbidity – TSS relationships to that measured in sections of the drain receiving discharge from developed land (Figure 6b). During civil works, the relationship was strong (R^2=0.66, $p<0.005$). This is comparable to the relationship previously found in Balannup Drain itself (Sutton 2017). In that previous study, R^2 at higher flows rates was improved when hydrological conditions were taken into account (antecedent storm conditions and rainfall intensity). We note that the Heron Park dataset spans across significantly higher TSS and turbidity values than measured in any previous study; a strong R^2 while covering these intense and intrinsically patchy storm conditions improves our confidence in the relationship. We note however that such storm conditions do not dominate the hydrological cycle, and that this study has demonstrated that sediment transport under baseflow conditions is significant. Therefore, the collection of additional data under high baseflow conditions is recommended to strengthen the relationship between TSS and turbidity.

Once the lots have been developed, there was no relationship between TSS and turbidity, and the overall TSS concentrations were lower (Figure 6b). The developed lots were no longer being actively disturbed, and landscaping and maturation of vegetation in the drainage channel likely trapped sediment. This landscaping of the drainage channel occurred at the same time as residential construction (but after civil works). In addition, mulch applied in residential gardens, and along the landscaped drainage channel, provides a source of dissolved organic matter; dark water was observed in all drainage from developed land. The decrease in sediment load and increase in colour, will significantly alter the relationship between TSS concentration and turbidity, as observed in Figure 6b.

4.3 Sediment discharged under baseflow conditions

To further explore baseflow dynamics along the drain between S1 and S2, under different hydrological conditions, we divided the additional flow contribution received from Stage 23 (i.e. flow measured at S2 minus flow measured at S1) by the area of Stage 23. This provided an estimate of water volume per unit area contributed to the drain. Under baseflow conditions in 2017, more flow was measured at S2 compared to S1, however the additional water measured at S2 declined from 21st May until the end of monitoring in early August (Figure 7**Error! Reference source not found.**a).

The monitoring period was extended into October in 2019, and an additional dynamic was captured. Under baseflow conditions, more flow was again measured at S2 compared to S1. The additional water measured at S2 declined from mid-June until mid-August, after which there was a marked increase in the contribution from the Stage 23 sub-catchment. This dynamic suggests that the drain, or the subsoil pipes discharging to the drain, were intersecting groundwater from the end of August.

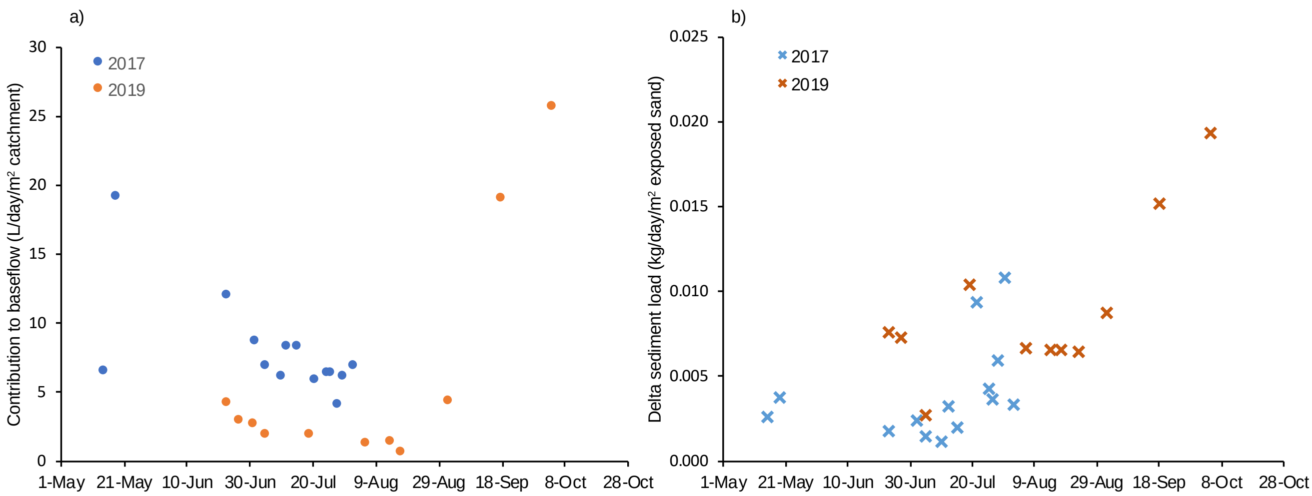

Figure 7 a) Additional flows measured at S2 compared to S1, under baseflow conditions in 2017 and 2019, relative to the Stage 23 sub-catchment area discharging to the drain; and b) change in sediment load per day per square metre of exposed sand, from S1 to S2 over the same monitoring periods in 2017 and 2019.

Figure 7b) highlights the concomitant increase in sediment load in 2019, when contributing flows increased after the end of August, most likely due to remobilisation of sediment by the higher contributing flows. We note that the drain section between S1 and S2 underwent extensive landscaping and planting between 2017 and 2019 (Figure 8). The possible impact of this landscaping on sediment loads transported through the drain, is discussed below.

a)

b)

Figure 8 Changing nature of the drain between S1 and S2 sampling stations, between a) July 2017 and b) in July 2019.

4.4 Sediment discharged during storm events

Turbidity was monitored at high frequency during about 20 storm events, across 2017 and 2019, to provide information on sediment mobilised by the events. Turbidity varied according to the size and intensity of the storm event, however a similar dynamic occurred from the start to the end of the event. An example of this dynamic is shown in Figure 9. The storm event triggered an increase in water level at both the inlet and the outlet (Figure 9a); during the event, the inlet water was often higher than the outlet. Turbidity readings at the outlet during event periods were typically higher than measured at the inlet (Figure 9b), indicating mobilisation of sediment from the adjacent catchment, or from within the drain itself (i.e. sediment that had been deposited in previous events).

After conversion of turbidity measurements into total suspended solid concentrations (through the relationship established in Section 4.2), the difference between TSS at the outlet and inlet provides an indication of how, and how much, sediment is mobilized during a single storm event (Figure 9c). After the initial small rainfall event on 30th June, there was a small net discharge of sediment at S2.

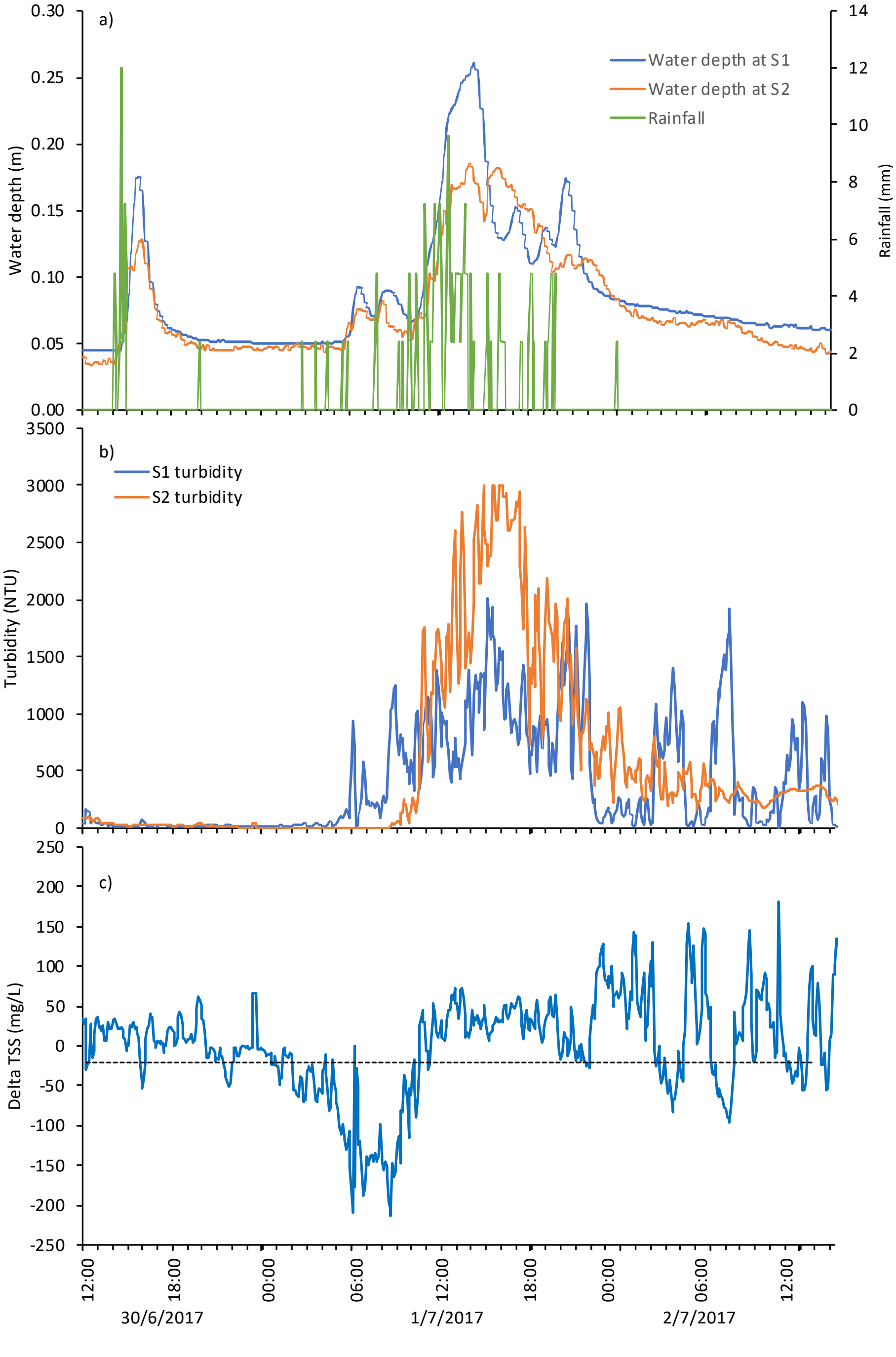

Figure 9 Monitored storm event in July 2017. a) Rainfall and associated water levels at the inlet and outlet, b) turbidity readings at the inlet and outlet, and c) differences in turbidity (Delta TSS) between S2 and S1. A negative value of Delta TSS indicates the drain is accumulating sediment, a positive value indicates the drain is releasing sediment, either from the drain itself, or from its catchment.

TSS concentrations were then multiplied by measured discharge rates, to estimate sediment loads discharged during storm and non-storm (baseflow) conditions. Sediment loads from five rainfall events, selected to cover a range of hydrological conditions are discussed below. Several large storms, and their non-event intervening periods were monitored between June and July 2017 and demonstrate indicative storm responses. Additional storms monitored in 2019 (not shown) confirmed the storm responses, though we were not able to capture the extreme events monitored in 2017. We have therefore focused detailed analysis on the 2017 dataset. We note that only two turbidity probes were available, and therefore only two sites could be monitored in any storm.

The event on 21-22 June 2017 (Figure 10a) displayed two peaks of approximately 170 L/s in response to a rainfall total of 41.2 mm. The rapid rising and falling limbs of the hydrographs reflected short burst of high-intensity rainfall at the site. The discharge hydrograph showed an early start of the event at the outlet (S2 station) from local runoff from Stage 23 entering the drain (at this stage of development the detention storage swale was under construction).

Cumulative TSS loads (i.e. mass of sediment in kg) for the same event indicated mobilisation of sediments at the outlet early in the event (i.e., from nearby surface runoff from Stage 23), and an increase in export towards the end of the event (i.e. mobilization of stored sediment from the drain). The TSS mean event concentration (i.e. the event volume-weighted mean concentration or EMC) increased from 81 mg/L to 97 mg/L from S1 to S2 locations, and a total of 70kg of sediment was discharged by this storm from the Stage 23 sub-catchment.

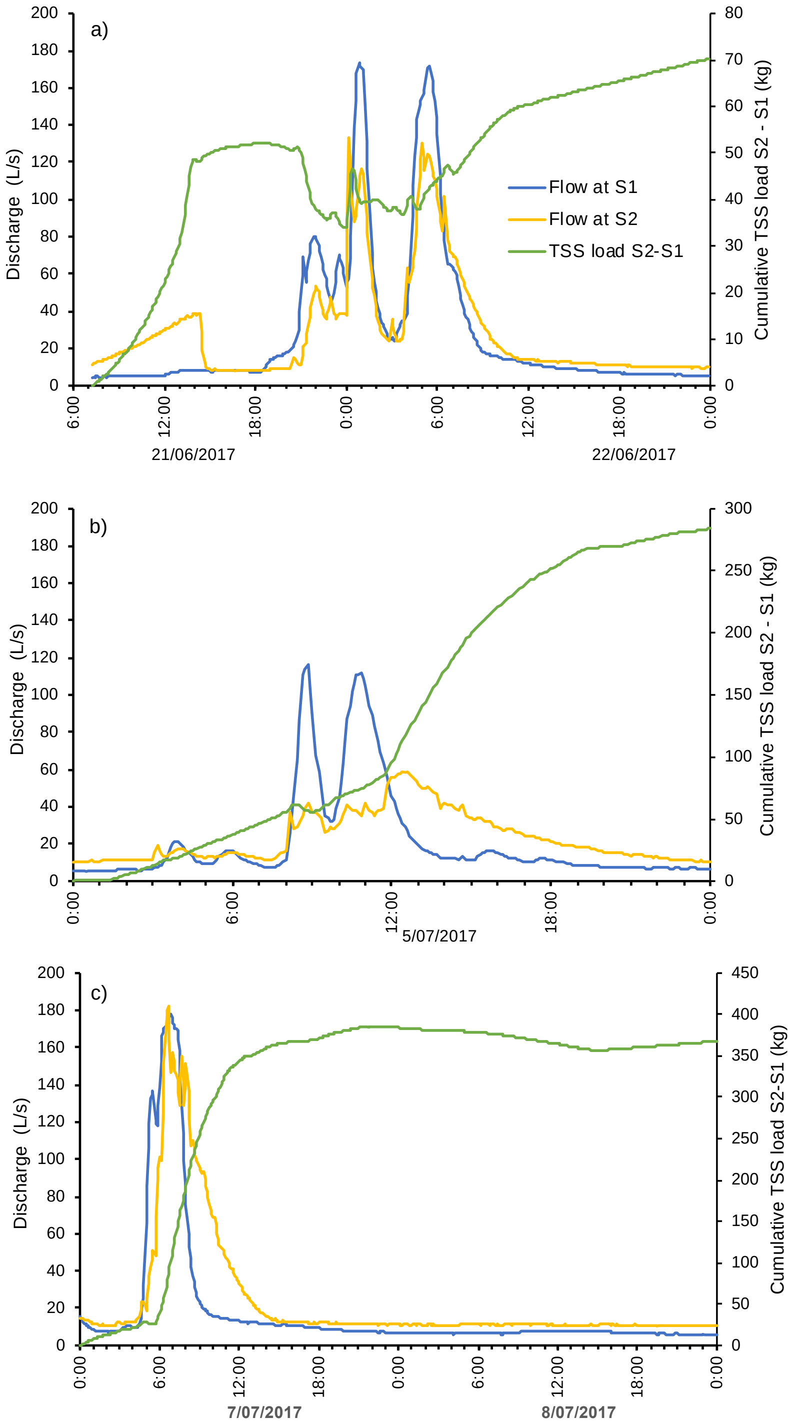

Figure 10 Discharge from S1 (blue) and S2 (yellow) across storm events on a)21st -22nd June 2017, b) 5th July 2017 and c) 7th – 8th July 2017. Also shown (green) is the cumulative sediment load per event delivered from Stage 23, or from the drain itself.

Figure 10b shows the hydrographs and cumulative TSS load for the storm event on 5th July 2017 in response to 18.2 mm of rain. Peak flow discharges at the outlet was smaller than those from the inlet; the peak attenuation and delayed recession for the outlet hydrograph could reflect the impact of the water storage in the detention swale (the landscaped swale was completed by this time, though vegetation was still at a minimum). The net discharge of TSS increased during the second peak of the event hydrograph, likely due to mobilisation of sediments from the drain. The EMC concentration increased from 85 mg/L at the inlet to 218 mg/L at the outlet location (S2). Over this storm event, almost 300 kg of sediment was sourced from the Stage 23 sub-catchment. A total of 40% of the development area at Stage 23 presented bare sand lots at the time of the event.

A single peak event hydrograph on 7th July 2017 resulted from a short duration-high intensity event totaling 14 mm (Figure 10c). The hydrograph response and the peak flow magnitude suggest that the event was localised and trigged runoff from surrounded areas in Stage 23; this is highlighted by the slower recession of the outlet hydrograph. Over this storm event, almost 380 kg was sourced from the Stage 23 sub-catchment. Despite the increase in sediment loading during the July 7 storm, the event mean concentrations were close to the previous event for S1 (85 mg/L) but lower at S2 (153 mg/L). Similar increases in TSS load were observed at other times when higher outflow rates (baseflow) coincided with hydrograph recession. Such increases in outflow sediment loads were therefore the result of higher flow rates (baseflow plus storm) within the drain reach and sediment being released from within-drain sources, likely deposited from previous storms. The combined TSS load from these two events (July 5 and July 7) reached 261 kg at the inlet station (S1), and 626 kg at the outlet station (S2).

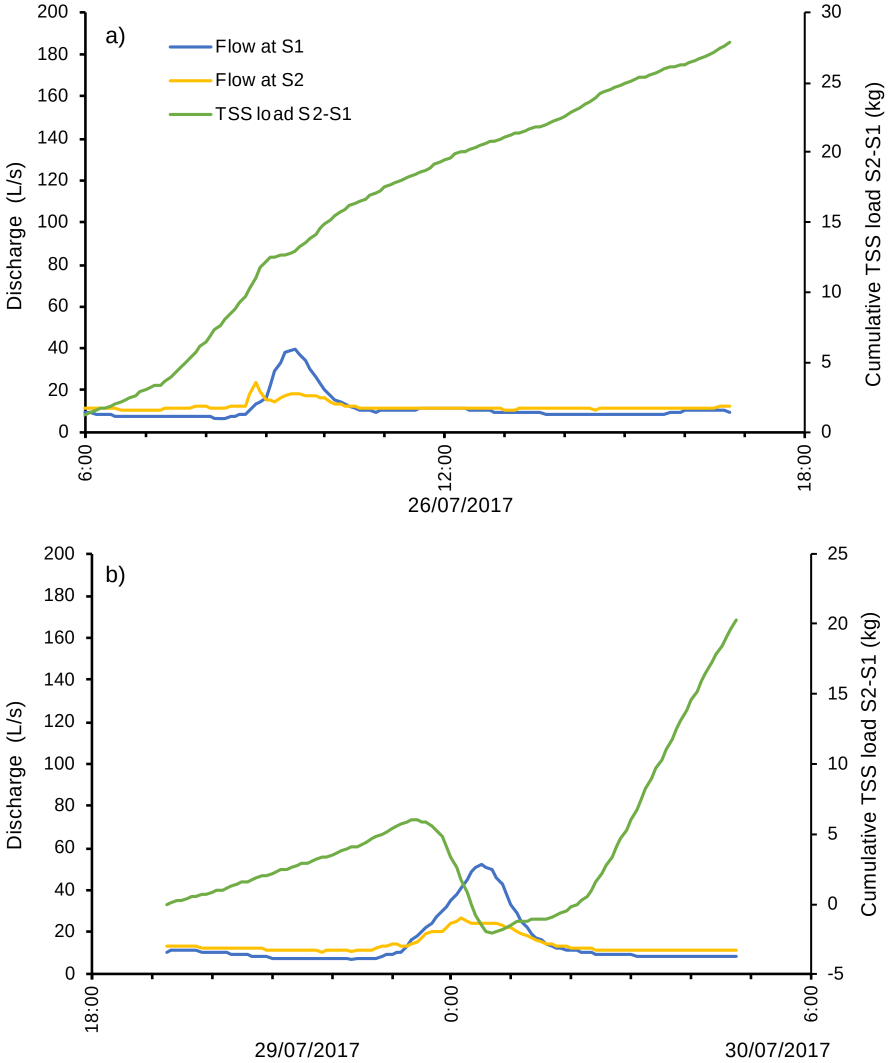

Figure 11 Discharge from S1 (blue) and S2 (yellow) across storm events on a)26th July 2017, and b) 29th July 2017. Also shown (green) is the cumulative sediment load delivered from Stage 23, or from the drain itself.

Flow and TSS load variability and magnitudes for two small events are presented in Figure 11. The event hydrograph on 26th July 2017 resulted from a rainfall totaling 1.6 mm (Figure 11a). The outlet hydrograph at S2 displayed a small peak ahead of that for the inlet location S1; this response was the result of local runoff (from Stage 23) entering the drain. The second peak flow of the S2 hydrograph was in response to S1 flow; the swale surface storage attenuated the inflow peak. The TSS load increased at the beginning of the event in response to local runoff from Stage 23 and after the inlet peak flow. Total TSS load discharged from the Stage 23 sub-catchment was close to 30 kg, with TSS EMC estimated values of 33 mg/L at S1 and 83 mg/L at S2.

Figure 11b shows event hydrographs resulting from a 2 mm rainfall event on 29th July 2017. As described for the previous event, the S2 hydrograph discharge slightly increased ahead of the increase in flow rate at S1. S1 peak flow was attenuated by the retention basin swale. Most of the increase in TSS load took place over the recession period of the outflow hydrograph and it was driven by an increase in TSS concentration. Similar to the event on 26th July, the total TSS load discharged from the Stage 23 sub-catchment was close to 30 kg.

4.5 Sediment loads from development activities

Baseflow conditions and over 20 storm events were monitored in 2017 and 2019. Under baseflow conditions, the central drain running through the Heron Park development transported on average 0.002 kg/day/m^2 exposed sand in the sub-catchment, when receiving water from stages undergoing residential construction and civil works (Table 3). The sediment transported under baseflow conditions likely accumulated in the drain intermittently during and since the last large storm event, and is being moved through the drain under low flow conditions.

Table 3 Comparison of sediment discharged from land under different development stages, per square metre of exposed sand in the sub-catchment. Values are averages across the two monitoring years 2017 and 2019.

Development activity in sub-catchment	Baseflow sediment discharge May - July (kg/day/m^2 exposed sand)	Baseflow sediment discharge Aug - Oct (kg/day/m^2 exposed sand)	Storm event sediment discharge May - Aug (kg/day/m^2 exposed sand
Residential construction and civil works	0.002	0.014	0.005

This sediment discharge was dependent on baseflow volumes which increased later in the season (as determined in 2019). After August, when baseflow volumes increased markedly, there was also an increase in sediment load to 0.014 kg/day/m^2 sand in the sub-catchment (Table 3).

There are two possible causes of this increased sediment discharge in late winter. The increased baseflows due to intersection of the seasonal groundwater could cause higher water velocities, which transport previously deposited sediment more effectively along the central drain. It is also possible that the higher baseflows flushed any sediment retained in the sub-surface branch network, into the drain. In both cases the higher baseflow likely flushed sediment that been deposited in the system during previous storm events. We note that this increase in sediment discharge occurred prior to the stockpiling of sand for spring construction activities.

Over the 20 storm events monitored in 2017 and 2019, sediment discharged during storm events was again calculated per square meter of exposed sand present in the sub-catchment at the time of the storm. Sediment was discharged during storms at approximately 0.005 kg/day/m^2 exposed sand; the magnitude of sediment discharge was dependent on storm characteristics. This was approximately twice the rate discharged under (low) baseflow conditions. As an example, during 2019, residential construction was being undertaken in Stages 24 and 28, with a total area of 8.4 ha of exposed sand. The data shows that this sub-catchment released 168 – 420 kg/day (105 – 265 m^3) of sediment to the drain, during storm events, with the magnitude of sediment discharged dependent on the magnitude of storm. No storm events were monitored later in the year, so we were unable to ascertain the impact of increased baseflow on storm-induced sediment transport. This requires further investigation.

In an average year, there are 282 days classified as baseflow days, and 83 days classified as stormflow days (Figure 12a). Stormflow days were defined as any rainfall event above 1mm (as this was observed to generate stormflow in the Heron Park drain). Flow-weighting was applied to storm events, to account for a storm hydrograph.

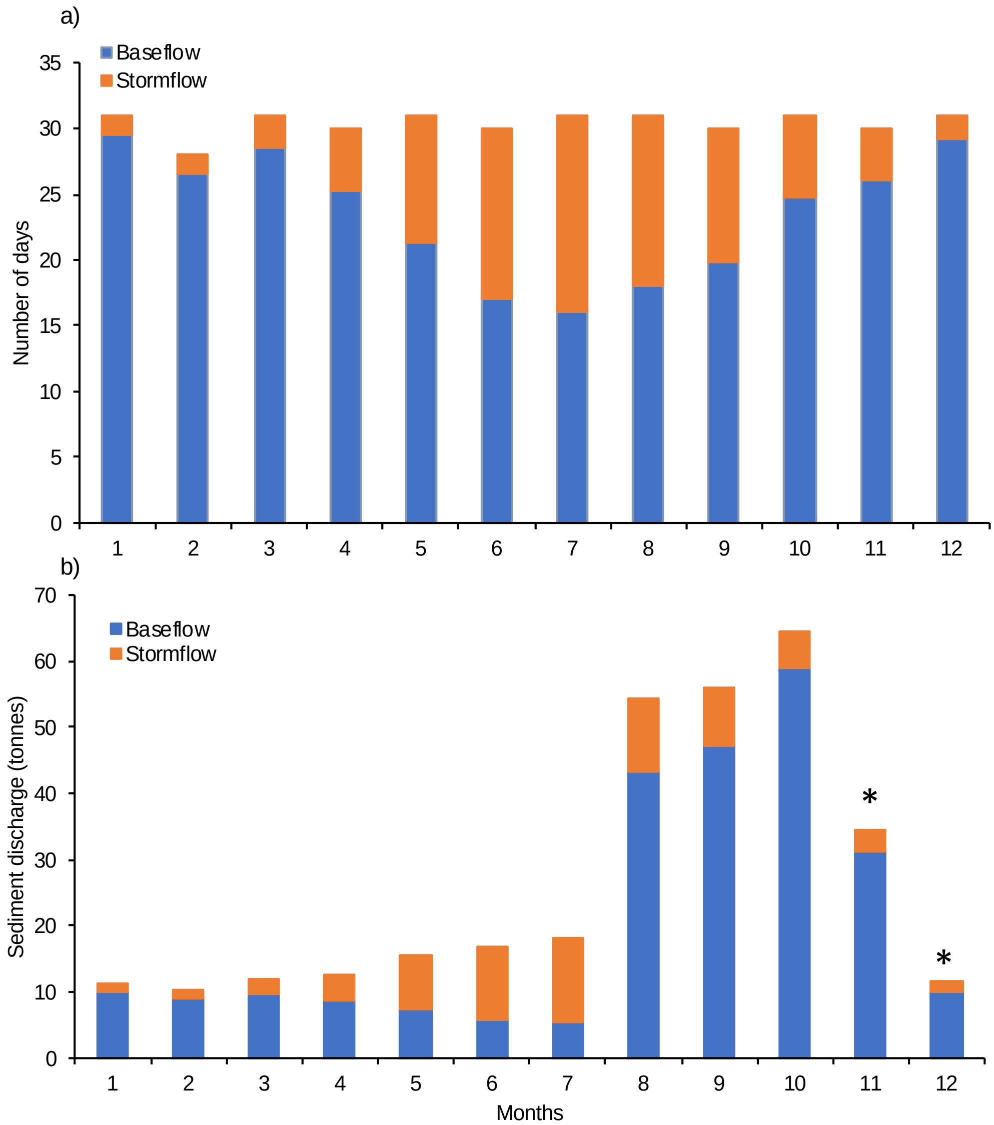

Figure 12 a) The distribution of baseflow days and stormflow days for an average rainfall year, as defined by rainfall data; and b) the estimated total sediment discharged from exposed sand across Heron Park in 2019. Asterisks highlight where sediment discharge estimates should be treated with caution due to unknown TSS – turbidity relationship under high baseflow conditions.

Heron Park had 25.9 ha of exposed sand in 2017, and 17 ha in 2019. Sediment discharges per day per area of exposed sand (the values in Table 3) were multiplied by the number of baseflow or stormflow days, and by the areas of exposed sand in 2017 and 2019. In total, an estimated 460 tonnes of water-borne sediment were discharged from the Heron Park site over 2017, and 306 tonnes over 2019. This amounts to 290 m^3 of sand in 2017, and 190 m^3 of sand in 2019. These rates of discharge equal sediment loss of approximately 17 tonnes/ha of exposed sand/year. When compared with recent estimates of 1.2 tonnes/ha/year from an agricultural catchment under a Mediterranean climate (Molina-Navarro et al. 2014), the result aligns with the USEPA conclusion that catchments undergoing urban development discharge sediment at a rate 10 – 20 times that of agricultural catchments.

It is interesting to note the distinct seasonality of sediment discharge from the site, driven by increased baseflows in August – October (Figure 12b). While storm-flow induced sediment transport may be highly visible, the ongoing discharge of suspended sediment by baseflows provides a significant chronic discharge, that may be frequently overlooked.

It is important to note that no flows or TSS concentrations were monitored on the site in January – April, and November - December, in either 2017 or 2019. Therefore, the sediment discharge under baseflows for those months were interpolated, and the values should be treated with caution, particularly the values for November and December. These values require confirmation with additional field data.

Due to high variability in the monitoring data, and the patchwork nature of development activity across the site, we were unable to estimate sediment load discharged from exposed sand in areas undergoing civil works alone, or during the bulk earthworks phase. This requires further investigation.

5. Conclusions and recommendations

5.1 Conclusions

Over 20 storm events were monitored in 2017 and 2019, along with baseflow conditions between the events each year. The project established a clear relationship between turbidity and total suspended solids, TSS, concentrations during active phases of development (civil works and lot-scale residential construction). Using the established relationship, we could use continuous turbidity measurements to establish sediment loads being discharged from active development sites, during storm events.

Five sites were monitored across 2017 and 2019, with three determined to define useful boundaries of development activity areas: S1 located at the inlet of Heron Park, S2 at the outlet of Stage 23, and S5 located close to the outlet of the development. Water levels and turbidity were measured at high frequency, and converted to flow rate (via a rating curve) and suspended sediment concentration (via the established turbidity – TSS relationship). Sediment loads could thus be estimated across a range of hydrological conditions.

While this project aimed to assess differences in sediment discharge across different construction activities, the variability in the sediment data was larger than any differences between activities; we therefore concluded that there was no difference in sediment discharge between the two construction activities tested: land under residential house construction, and land undergoing civil works. While erosion of individual piles of sand from individual lots is very visible after storm events (the pile is decreased in height), the sand erosion across a large expanse of sand is less visible. This work confirmed prior findings that water-borne erosion is a shared responsibility across multiple stakeholders, which has implications for the regulation and management of water-borne sediment, as discussed below.

The rate of sediment discharge between sampling sites, during storm events and under baseflow conditions, was calculated per square meter of exposed sand present in the sub-catchment. During storm events, sediment was discharged at a rate of 0.005 kg/day/m^2 sand.

When baseflow was low, from February – July, sediment was discharged at a rate of 0.002 kg/day/m^2 sand. Interestingly, when baseflow increased, from August – October most likely due to intersection with seasonally high groundwater, there was a concomitant increase in sediment discharge to 0.014 kg/day/m^2 sand. This increased sediment discharge was likely due to higher volumes of water flushing out sediment previously deposited into the system. In September, it was also observed that there was increased delivery and accumulation of exposed sand in the sub-catchments, in anticipation of construction work during the spring/summer. Spring storm events could therefore wash sand from these stockpiles into the drainage network and contribute to sediment discharge during this period; this process should be further investigated.

These rates of sediment discharge were applied to an average rainfall year, to determine that sediment is discharged at a rate of approximately 17,000 kg/ha of exposed sand/year. This can be compared to measured sediment fluxes of 350 kg/ha/year from an agricultural (grazing) catchment in Western Australia (McKergow et al. 2001); after restoration of the stream riparian zone, this agricultural sediment export reduced to 9 kg/ha/yr (McKergow et al. 2001). We note that the differences between the discharge rate measured at Heron Park, and that measured by McKergrow et al. (2001), is broadly in line with the USAEPA (2000) estimate that construction activities discharge sediment at rates 10-20 times the rate from agricultural lands, and 1000-2000 times the rate from forested land. For the sites monitored in Western Australia, land under construction was discharging sediment at approximately 50 times the rate from agricultural land.

Across the Heron Park site, the measured sediment discharge rate amounted to a total of 460,000 kg (290 m^3) in 2017, and 306,000 kg (190 m^3) in 2019. One cubic metre of sand fill costs developers up to $25 for purchase, delivery, placement and compaction; thus the cost to the developer of losing 200-300 m^3 per year is only $5,000-$7,500.

In contrast, the cost borne by high growth local councils can however reach over $600,000 per year for managing water-borne sediment discharge from new subdivisions (www.perthnrm.com/2019/06/stf-article-costofcontrol, accessed February 27 2020). Other councils have dredging reported costs of $15 – $80 per tonne of sediment, depending on the ease of access to the site and difficulty of the dredge. Using this costing, if all the sediment discharged along the Heron Park drain in 2017 and 2019 (estimated at 766 tonnes) were released to waterways, it would cost $12,000 – $60,000 to remove/dredge.

The work of McKergow et al. (2001) demonstrated that, with appropriate planting adjacent to agricultural drainage lines, the sediment discharge could be reduced to almost nothing. This aligns with advice from sediment management manuals from Australia and overseas, that recommend temporary planting of exposed sand areas and drainage lines, right at the start of land disturbance for urban development. The retention of sand on site that would otherwise be lost to erosion, would provide an additional resource for use in the development, and would significantly reduce the cost to local councils and the Water Corporation of dredging sediment from downstream drains and waterways.

5.2 Recommendations

The data collected during this research project, and previously published work, has highlighted that active management of water-borne sediment is essential during all phases of land development, from initial earthworks, through to civil works, landscaping and finally house construction. The field data collected during this project did not show significant differences between sediment discharged per area, from land undergoing residential construction, and land predominantly undergoing civil works. This highlights the need for shared responsibility for management of water-borne sediment discharge from urban development. This shared responsibility is more challenging to regulate, and any recommended sediment management practices must account for this.

Currently, there is private financial benefit to land developers, builders and consumers from urban development, yet the cost of expensive on-going management of water-borne sediment arising from this urban development, is predominantly borne by the local and state government, and therefore the public. This private benefit – public cost needs to be further examined, along with the financial, ecological and social costs of environmental degradation caused by water-borne sediment, as best practice sediment management practices are considered.

Management practices that prevent both air-borne and water-borne soil loss should be implemented. For example, the rapid, temporary revegetation of exposed soil, or retention of natural vegetation, is recommended at all stages of development. In addition, the implementation of temporary swales at drain outlets during development, provides an end-of-pipe prevention of sediment discharge to downstream waters. A comprehensive list of appropriate sediment management practices, across different stages of urban development, was provided in ESS (2010).

This work has highlighted some key data and knowledge gaps, and the need to consolidate the findings of the project. There are two ways to achieve this: 1) through monitoring activities and 2) through numerical modelling.

Monitoring is essential to determine, in order of priority:

- Sediment discharge from land undergoing bulk earth works. This monitoring activity would require a new study site.
- Event-based sediment discharge when baseflows are high. At present no data exists for this condition. In addition, confirmation is needed that the turbidity-TSS correlation established for storm events from construction activities, is still applicable to high baseflow conditions during the spring. This monitoring could be undertaken at Heron Park.
- Sediment load accumulation and export associated with civil works areas with exposed sand. Short-term targeted monitoring should be undertaken, of sediment accumulation and export, during and after

completion of civil works areas, with exposed sand. This land use will be present until the completion of the Heron Park development, and thus provides opportunities to build on the findings of this report.
- Sediment transport and export along the minor drainage network and side pits at Heron Park. This includes short-term monitoring at times when baseflow is high.

Modelling of in-drain sediment transport is required to determine any remobilisation of bedload sediment (i.e. sediment that has previously accumulated and stored in the drainage network), that may occur in addition to the transport of suspended sediment. It is currently unknown what magnitude of storm events or baseflow is required to flush bedload sediment out of the system. A numerical model would allow exploration of the effect of different hydrological conditions on total sediment transport (suspended and bedload).

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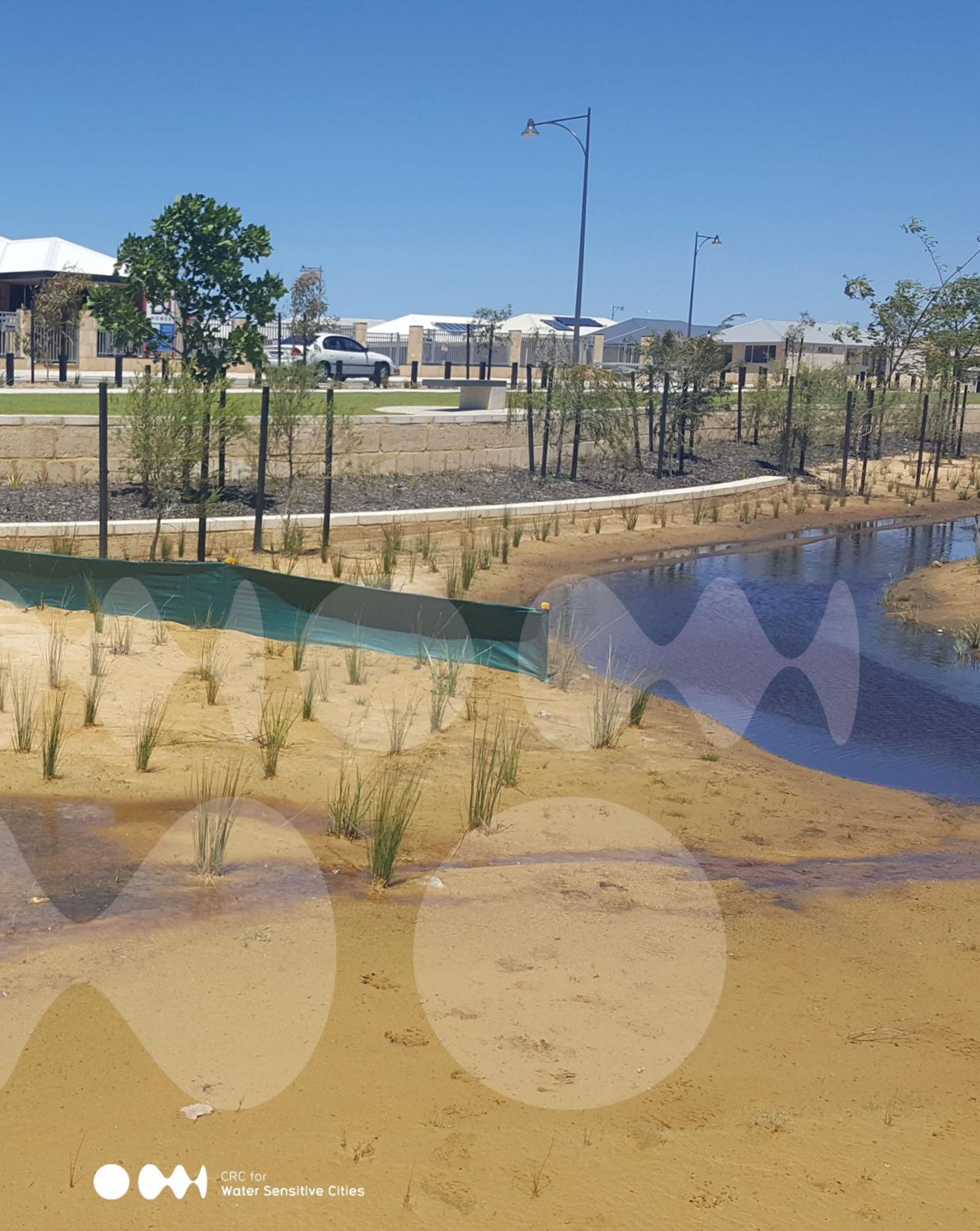
Appendix

Table A1: Practices recognized as providing effective management of sediment erosion in Western Australia, and the stage at which they are generally most effective (modified from ESS 2010). Practices focused on management of air-borne sand erosion have not been included.

Best management practice	Subdivision – site clearing and bulk earthworks	Subdivision – infrastructure and lot construction	Development – building construction
Minimise clearing of natural vegetation			
Watering			
Construction period/earthworks programmed for periods of lower stormwater runoff[1]			
Works undertaken so that a minimum amount of ground is disturbed at any one time			
Perimeter fencing			
Brushing			
Hydro-mulching			
Seeding			
Replacement of topsoil to encourage revegetation			
Temporary surface water management measures including sediment basins			
Signs and fencing restricting access			
Regular street sweeping			

[1] ESS (2010) recommended that land disturbance be undertaken during times with low winds, to minimize wind-borne sand erosion. This recommendation has been adapted for management of water-borne sediment erosion.

Stabilised and controlled vehicle access			
Location and protection of stockpiles			
Verge cover			
Geotextile sausage/socks			



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